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Two Dimensional (2D) Slope-Stability Analysis- A review

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Abstract: ***Slope stabilizing is a major challenge for the geotechnical engineers. It was since 1930s, the two-dimensional (2D) slope stability methods are the most widely used methods of analyzing the slopes due to their simplicity. Many researchers have developed various techniques and methods to analyze the stability of slopes. The traditional method of slope stability is the limit equilibrium method (LEM) where a factor of safety (FOS) is calculated to predict the stability of slopes. Some other researchers develop more powerful techniques of analyzing slope stability by using numerical methods like finite element method (FEM), finite difference method (FDM), strength reduction method (SRM), gravity increase method (GIM), limit analysis, etc. The analysis and design of slopes requires a thorough understanding of the problem and failure mechanism so as to choose the most appropriate method of slope stability. This paper basically focuses on the literature review of 2D slope stability by various researchers. The literature review is done based on two approaches- the deterministic approach and the probabilistic approach.***
Keywords: Limit equilibrium method, Finite element method, Strength reduction method, Deterministic approach, Probability approach.

I. INTRODUCTION

Stability of natural and man-made slopes such as roads and railway embankments, road cuts, etc. are causing a serious problem to the geotechnical engineers. These vulnerable slopes are making the problem worst and hence, need to be analyzed and designed very carefully. The two-dimensional slope stability methods are the most commonly used methods because of their simplicity. The most commonly used two-dimensional slope stability method is the limit equilibrium method (LEM) where a FOS is calculated to predict the stability of slopes. These methods remain popular because of their simplicity and the reduced number of parameters they require, which are slope geometry, topography, geology, static and dynamic loads, geotechnical parameters and hydrogeologic conditions. The use of deterministic methods like finite element method (FEM), finite difference method (FDM), strength reduction method (SRM), gravity increase method (GIM), limit analysis, etc. are increasing at a fast rate with the advancement of computer performance. These methods are having the advantage of modeling the slopes with a higher degree of realism (complex geometry, loading sequences, presence of reinforcement material, action of water, soils having higher complexities) and to better envisage the deformations of soils in place (Baba et al., 2012).The basic purpose of the deterministic method of slope stability analysis is to determine the location of the critical slip surface and to find the FOS against failure. If the FOS is determined to be large enough, then the slope is judged to be stable (safe). But if the FOS is equal to 1.0 or less than that, it is considered to be unsafe. But these deterministic methods failed to explain the uncertainties present in the soil slope. As a result, the probabilistic methods started growing as they are able to explain the uncertainties present in the soil slope. A review of the literatures done by the various researchers in the field of 2D slope stability has been discussed below. This paper mainly focuses on the deterministic and the probabilistic approach of slope stability analysis.

II. LITERATURE REVIEW

A. Based on Deterministic Approach

The deterministic approach involves the various techniques like LEM, FEM, FDM, etc. which involves in determining the FOS of the soil slope. In the LEM, the equilibrium of a soil mass ready to fail under the influence of gravity is examined. As a result, in this method, the failure of soil slope can be considered as that condition where the driving forces (or moments) exceeds the resisting forces (or moments). The force equilibrium is considered for translational or rotational failures whereas the moment equilibrium is considered only for the rotational slides. For LEM, the whole sliding body of the soil mass is divided into ‘n’ number of vertical slices and hence, the method is named as method of slices. The stresses (normal and tangential) at the bottom of each section are determined by considering the equilibrium conditions of forces acting on each of the section. Many researchers have used different

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assumptions for making the problem determinate and therefore, they have come up with various equilibrium equations. The simplest solution of the slope stability problem was formulated by Fellenius (1936) where he ignores all the interslice forces and in addition, the method does not satisfy the equilibrium of the individual slices. This leads to erroneous results in the calculation of effective stresses at the base of slice. After this, Bishop (1955) established a new solution which satiates the vertical force equilibrium and moment equilibrium about the center of the circular slip surface. But the major disadvantage of this method is that it cannot be used for non-circular slip surfaces. Janbu (1957) developed a new method of solution of slope stability which satisfies the vertical force equilibrium for each slice. But the method fails to satisfy the overall moment equilibrium of the slide mass. The solution developed by Janbu is over-determined and later he developed a correction factor f_0 to account for this inadequacy. It was in 1965 when Morgenstern and Price developed a new method of analyzing the slope stability which is perhaps the best known and most widely used method. This method considers the vertical and horizontal force equilibrium as well as the moment equilibrium for each slice. This method is very advantageous as it can be used for any shape of the slip surfaces. Spencer (1967) established a method similar to Morgenstern and Price method which can be used for any shape of the slip surface. The method assumed the inter slice forces to be parallel i.e. they are having the same inclination. Fredlund and Krahn (1977) developed factor of safety (FOS) equations for solving a composite failure surface, partial submergence, line loading and earthquake loading conditions by comparing the various 2D slope stability methods. Sharma (1979) introduced a different method which not only satisfies the force equilibrium but also the moment equilibrium. The approach of this method is a bit different as it considers the seismic coefficient (k_c) to be unknown and the FOS to be known. Some of the researchers classified the limit equilibrium theorems into upper and lower bound solutions, but the studies utilized mostly the upper bound method. This is solely because of the difficulties in computations involved in lower bound analysis. Some of them include Chen (1975), Karal (1977), Donald and Chen (1997), Yu et al. (1998) and Kumar (2000). The limit equilibrium methods are economical to use and produce good results for simple geometries. But for complex geometries, calculation work becomes very challenging as it involves long iteration procedure to satisfy the equilibrium conditions. This discrepancy is removed by some of the researchers by introducing FEM for slope stability. One of the earliest FE method of slope stability for was introduced by Smith and Hobbs (1974) and the method was used only for $\varphi_u = 0$ soil. Zienkiewicz et al. (1975) used FEM to find the FOS for a c-φ soil slope and the results obtained was very satisfactory with slip circle solutions. Griffiths (1980) used FEM to show consistent slope stability results for an extensive range of soil types and geometric conditions as compared with the charts of Bishop and Morgenstern. Griffiths and Lane (1999) again used the FEM in combination with Mohr-Coulomb stress-strain method to examine the stability of slopes and failure was measured as the situation when no convergence occurs within the specified number of iterations. Rabie (2014) carried out a comparison study between the LE methods and FE methods of calculating the FOS under the effect of heavy rainfall and finally it is concluded that the classical LE methods are highly conservative compared to FE approach.

FEM has been used along with more advanced techniques such as strength reduction and gravity increase method. Matusai and San (1992) combined FEM and strength reduction method (SRM) for slope stability analysis and on comparing the results of the two they came up with the conclusion that the adopted method agrees well with the Bishop's method when the total shear strain is used. Cheng et al. (2007) studied about LEM and SRM by comparing the location of critical slip surface and the FOS results and conformed that the results of SRM and LEM holds good for simple homogenous soil slopes but fails to determine the other slips surfaces which are less critical than SRM solution. The use of gravity increase method has also made some remarkable contributions. On implementing the gravity increase method into the Realistic Failure Process Analysis (RFPA) code using finite element analysis, it has been observed that the numerical results hold good with the experimental results (Li et al. (2009)).The implementation of the non-linear Hoek-Brown strength reduction in slope stability by Fu and Liao (2010) resulted that the variation of the instantaneous cohesion and friction angle reflect well under different stress states. Sternik (2013) made a comparison study of analyzing the FOS using strength reduction method, gravity increase method and Modified Bishop's method and found the results to be in good agreement. Moreover, he also found that the FOS obtained by gravity increase method is an overestimation when linear Mohr-Coulomb criterion is used.

It has been found from the literature survey that LEMs perform better than the FEMs for simple cases and have lower FOS compared to FEM. The reason can be the assumptions made during the LEMs where a critical slip surface is assumed and equilibrium equations are satisfied for that particular case. However, this may not be the critical sliding surface every time. Hence, the results produced by LEM need to be optimized for minimum value of FOS. This lead to the requirement of more advance methods in the analysis. Many researchers started incorporating optimization methods in existing limit equilibrium and numerical methods. Bolton et al. (2003) used leap frog optimization procedure for analyzing stability of slopes. This technique helps in finding the location of the critical slip surface in Janbu's simplified and Spencer's method. This technique also helps in finding the failure surfaces contained within weak layers within the slopes. Again, Chen et al. (2003) formulated the upper bound limit analysis as a nonlinear programming problem based on FEM and used sequential quadratic algorithm to minimize the FOS. The method has the advantage in modeling non-homogeneous soil conditions and complicated boundaries. It has been observed that simple genetic algorithms are better than the other optimization methods in slope stability analysis of slopes having complex geometrics. Zolfaghari et al. (2005) demonstrated this in detail by solving Morgenstern and Price method with the help of simple genetic algorithm. They also included the option surcharge load and earthquake forces in the method to enable it to a more comprehensive slope stability analysis. Some other powerful optimization techniques have also been developed by various researchers. Some of the powerful methods of optimization techniques include the heuristic algorithms by Cheng et al. (2007), ant colony optimization, simulated annealing, simple and modified harmony search by Cheng et al. (2007), gravitational search algorithm by Khajehzadeh et al. (2010) and imperial competitive algorithm by Kashani et al. (2015). Kashani et al. compared all the optimization methods mentioned here and concluded that the imperial competitive algorithm gives the lowest FOS for the same problem compared to other methods. This kind of algorithms heightens the accuracy in searching the location of the critical slip surface and the value of FOS.

From the above discussion, it can be concluded that the deterministic methods are used for determining the FOS and location of the critical slip surface of a slope. This FOS is then used as design parameters for designing the slope. But practically a single FOS for the whole slope never exits. The site conditions may vary a lot at different locations. There may also be sometimes presence of uncertainties in the analysis like uncertainties in the soil parameters, ground water conditions, vegetation and surrounding of the slope. But the deterministic methods failed to undertake the uncertainties present in the soil slope. Hence, more rigorous methods are required for analyzing the slope which can take into account the above uncertainties.

B. Based on Probabilistic Approach

The stability of slopes can also be defined based on the concept of probability of failure. To take into account the various uncertainties the probability concept is very reliable to use. Probability analysis of slopes are gaining popularity in the recent years. In the last few decades, some remarkable work has been published in the field of probabilistic approach of slope stability. A few of the research work on probabilistic approach using first order second moment (FOSM) method include Wu and Kraft (1970), Cornet (1971), Alonso (1976), Vanmarcke (1971), Tang et al. (1976), Vanmarcke (1980), Li and Lumb (1987), Luckman et al. (1987) and Halim and Tang (1987). It was Tobutt (1982) who first demonstrated the Monte-Carlo simulation (MCS) technique for slope stability analysis. Further, Christian et al. (1994) used the first order method and the application of probability concept for analyzing and accounting the uncertainties present in the slope stability.

The probability of failure is calculated on the basis of critical slip surface obtained from the deterministic method by the initial researchers. After that it was Hassan and Wolff (1999) who stated that the critical slip surface having minimum FOS may or may not be the critical surface of the maximum probability of failure. Thereafter, Chowdhury and Xu (1995), Liang et al. (1999) and Bhattacharya et al. (2003) continued on their research work by considering the critical slip surface to be the surface with minimum reliability index.

Malwaki et al. (2000) studied the comparison between FOSM method and MCS method for calculating the reliability index based on various approaches like ordinary method of slices, Bishop’s method and Janbu method. The results obtained by them showed that FOSM method requires less computation and less time compared to MCS method but MCS method is found to be more powerful and more accurate method. Ramly et al. (2002) also used MCS method for probabilistic analysis of a slope by taking spatial variability of soil parameters into consideration and finally compared the results with FOSM method. They found that the method gives reliability values less than FOSM. The similar result was obtained by Griffiths (2004) on comparing simplified probabilistic method for finite element analysis and Monte Carlo simulation for finite element non-linear elasto-plastic analysis. It has also been found by Hong and Roh (2008) that the reliability of a slope can be sensitive to the probability distribution types for the input parameters. Hence, the FOSM method should not be used until the probability of failure is large.

In the recent years, advanced methods have been developed using Fuzzy Logic Sets and Artificial Neural Network (ANN) in the reliability analysis. Habibagahi and Meidani (2000) used fuzzy sets for dealing the uncertainties present in the soil and developed a computer program which can calculate the FOS based on the concept of domain interval analysis. The proposed reliability index gives a better understanding of the failure risk than does a conventional FOS alone. The use of ANN in the reliability analysis was done by Cho (2009). The study gives the conclusion that the results of ANN based response surface model does not depend on the choice of the method like finite element, finite difference or limit equilibrium methods. One other advanced optimization technique named “Harmony search meta-heuristic algorithm” used by Khajehzadeh et al. (2010) in the field of reliability analysis of slopes was found to be very advantageous because of its simplicity and its ability to construct a new vector from a combination of all existing vectors. Reliability analysis also depends upon the choice of the type of probability distribution i.e. normal or lognormal distribution for random variables, Metya and Bhattacharya (2012). Normal distribution of random variables gives lower reliability index compared to lognormal distribution. Singh et al. (2013) carried out a slope stability analysis based on probabilistic approach in Amiyan landslide area, Uttarakhand. The slope was simulated using FEM and LEM and results were compared with the probabilistic method and it is found that the results of numerical simulations matched with the field observations.

Thus the probabilistic approach seems to be more powerful compared to the deterministic approach in defining the stability of a slope. The probability of failure or the reliability index gives much more information about the failure than the deterministic approach. But the major problem of probabilistic approach is that more soil data is required to plot the distribution graph of each design parameter as against a single value of FOS. Moreover, a well expertise is required to analyze the reliability results and to choose a suitable and economic design factor for the slope.

III. CONCLUSIONS

Various available slope stability methods are discussed in this paper. It can be concluded from the above discussions that LEMs are simple and less accurate compared to other deterministic methods like FEM, FDM, limit analysis etc. These deterministic methods cannot take into account the uncertainties involved during the slope stability analysis. On the other hand, these uncertainties are taken care of by the probabilistic methods. The probability of failure or reliability index gives much more information than the FOS used in the deterministic approach. Further, it has been seen that modern optimization techniques are very useful in minimizing the FOS or reliability index or in locating the critical slip surface either deterministic or probabilistic.

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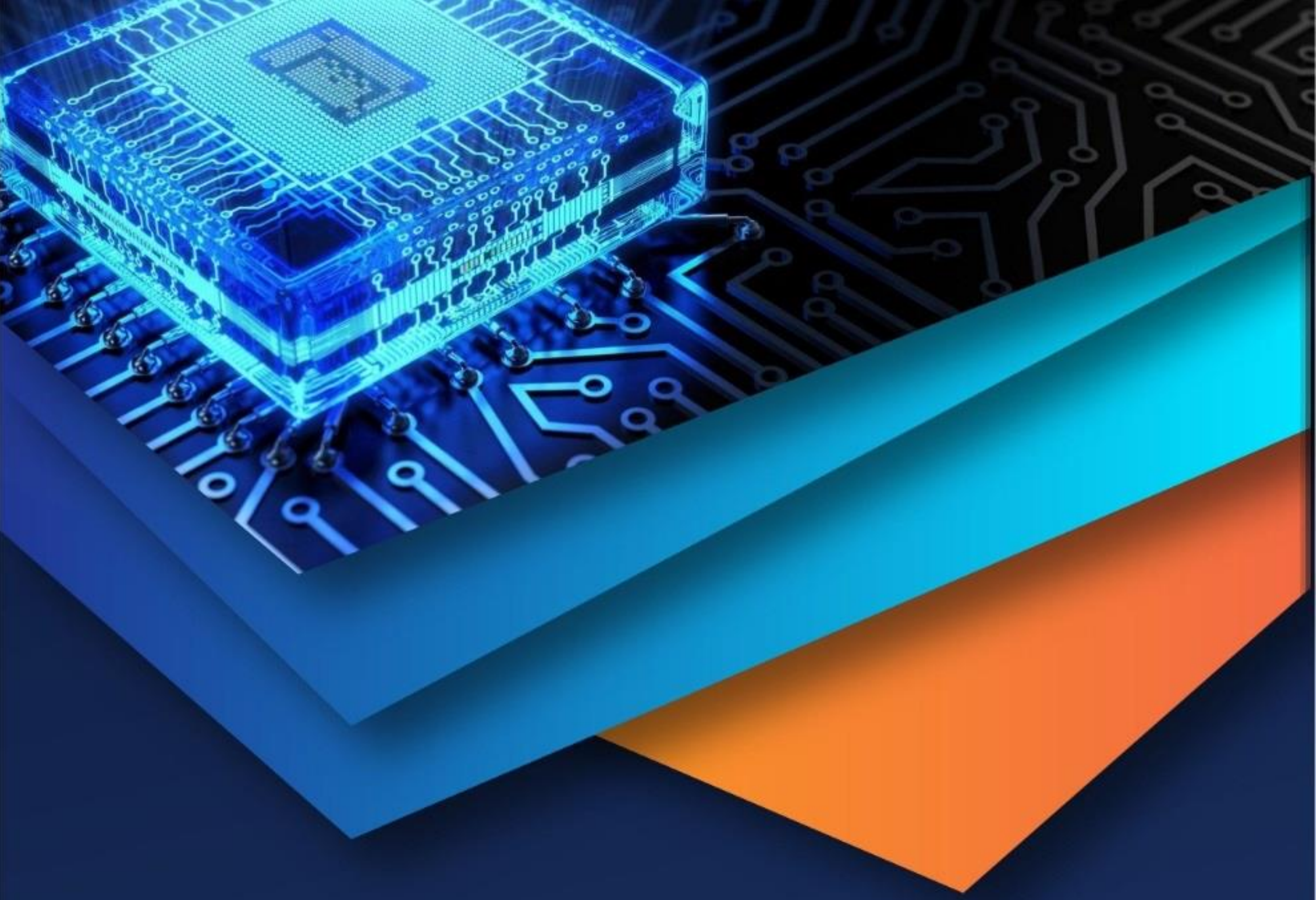

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